



Antibacterial Efficacy of Fe doped ZnO nanoparticles and Cinnamon Essential Oil against Multidrug Resistant Pathogens (A Review)

M. Musa Mubashar¹, Shoaib Shafqat², Munawar Ali³, Zahid Shahbaz⁴ and Shahid Shahbaz⁵

¹Institute of Microbiology, University of Agriculture Faisalabad, Pakistan

²Faculty of Public Health, Universitas Indonesia, Depok, Indonesia

³College of Veterinary Medicine, Nanjing Agricultural University, Nanjing, China

⁴School of Bioengineering, Dalian University of Technology, China

⁵Faculty of Medicine, Selcuk University, Turkey

*Correspondence: mmmusa7672@gmail.com

ARTICLE INFO

ARTICLE HISTORY: CVJ-25-1113

Received: September 26, 2025

Revised: November 05, 2025

Accepted: November 11, 2025

Published online: November 13, 2025

Key words:

Antibacterial Mechanisms

Antimicrobial Resistance

Escherichia coli

Iron-Doped Zinc Oxide

Cinnamon Essential Oil

Staphylococcus aureus

Nanoparticles

ABSTRACT

The emergence of increasing antimicrobial resistance (AMR) compels the development of new antibacterial strategies at a timely manner. In this review, the antibacterial activity of iron-doped zinc oxide (Fe-doped ZnO) nanoparticles and cinnamon essential oil (CEO) mixture was investigated and the mechanism of action between two clinically indicative pathogens, *Staphylococcus aureus* (Gram positive bacterium) and *Escherichia coli* (Gram negative bacterium). This article is based solely on peer-reviewed academic research articles that describe synthesis and characterization of each agent, or any antibacterial activity including minimum inhibitory concentrations (MIC), minimum bactericidal concentrations (MBC). The major focus is given to explain their different mechanism of actions including the production of reactive oxygen species (ROS), disruption of the cell membrane and suppression of metabolic pathways. Moreover, there is also a discussion on whether such antibacterial components may have a synergistic interaction by combination and how the combination may enhance antibacterial actions, and neurotrophic biofilm development in countering bacterial resistance through a multi-pronged approach. This review also discusses the relative efficacy of these agents, benefit of their use with AMR, the current difficulty of their use with AMR and the toxicity and the necessity that further in vivo experimentation and standardization is required. The significance of this review is demonstrated by the near miraculous antibacterial potential of these new components and possible alternatives to traditional antibiotics in the therapeutic approach to bacterial infections.

To Cite This Article: Mubashar MM, Shafqat S, Ali M, Shahbaz Z and Shahbaz S, 2025. Antibacterial efficacy of Fe doped ZnO nanoparticles and cinnamon essential oil against multidrug resistant pathogens (a review). Continental Vet J, 5(2): 167-176. <http://dx.doi.org/10.71081/cvj/2025.054>

INTRODUCTION

AMR is a global health problem, and a new affordable and inventive remedy to this burden falls outside the contemporary reach of antibiotics (Salam et al., 2023). The process has grown alongside of growing resistance of microorganisms to antibiotics, i.e., even more desirable alternatives are required. Recent studies by the public health organizations describe the drastic impact of AMR on economy and society - and project it may cause the death of many millions of individuals per year, unless there is an active response put in place (Tang et al. 2023). AMR impacts all sectors, especially the intensive animal husbandry system that uses antibiotics regularly (Van Boeckel et al., 2015).

The improper use of current antibiotics also seriously contributes to this crisis, leading to an increase and rapid spread of highly resistant bacterial strains, especially the methicillin-resistant *Staphylococcus aureus* (MRSA) in both clinical and community-based locations (Algammal et al., 2020). High frequencies of antibiotic-resistant *S. aureus* and methicillin-resistant and vancomycin-resistant, and linezolid-resistant strains doubt the clinical practice by drawing an urgent need to identify alternative treatment methods (Azhar et al., 2017). The insufficiency of traditional approaches, especially against resistant organisms and biofilm-implicated pathogens, produces multiple research gaps that nanotechnology and natural products are trying to fill. This fact lifts AMR out of being

a mere health issue and turns it into a systemic economic and societal burden, requiring a paradigm shift in the development of antimicrobials. The global antibiotic production is categorized into two, 50 percent of which is used to treat animals with antibiotics, mainly to defend against colibacillosis in poultry and mastitis in dairy cows (Tang *et al.*, 2017).

The use of nanotechnology is acknowledged as a revolutionary change and an opportunity to have a new generation of alternatives to control bacterial infections and create so-called nano-antibiotics (Raghunath *et al.*, 2017). Silver, gold, copper, selenium, zinc oxide (ZnO), titanium dioxide (TiO₂), calcium oxide (CaO), and magnesium oxide (MgO) nanoparticles (NPs), among other metal and metal oxide nanoparticles, have been proposed as novel antimicrobial agents (Prabhu *et al.*, 2012). Their nanoscale peculiarities, such as a large surface area to volume ratio, allow interacting with the bacterial cells more effectively and provide multi-level mechanisms of action, which is why bacteria find it much more difficult to develop a resistance to it. The mechanism of action of these nanoparticles can be varied, such as cell wall breakage, membrane damage in the cytoplasm, the formation of reactive oxygen species (ROS), enzyme inhibitory action, and the modulation of gene expression (Lakshmi Prasanna *et al.*, 2015).

At the same time, plant-derived natural products, especially essential oils (EOs), are also receiving a lot of attention as potentially valuable sources of new antibacterial agents. Cinnamon (and other essential oils) have often shown strong antibacterial activity, and this is commonly because they have complex and diverse chemical compositions (Visan *et al.*, 2024). Combined research in nanotechnology and natural products is a strategic change in modeling antimicrobial development. Nanoparticles have increased delivery capabilities and multi-mechanism of action, and essential oils have a wide variety of bioactive compounds (Patra *et al.*, 2018). The combination has the potential of exhibiting synergistic effects that defeat single-target resistance mechanisms.

Staphylococcus aureus (*S. aureus*) is a pathogenic Gram-positive microorganism, and it can cause a wide range of infections including pneumonia, endocarditis, osteomyelitis, septicemia, and sepsis (Taylor *et al.*, 2017). The emergence of antibiotic-resistant strains has increased exponentially with the most notable one being methicillin-resistant *S. aureus* (MRSA). It is a major burden in both healthcare facilities and society. The use of antimicrobial as doses on bovine mastitis has seen the emergence of antimicrobial-resistant *Staphylococcus aureus* which has become difficult to treat and can lead to animal-to-human transmissions, with methicillin-resistant *Staphylococcus aureus* (MRSA) appearing to be capable of two-way transmissions (Fessler *et al.*, 2011; Mphahlele *et al.*, 2020). Strong biofilm production in *S. aureus* also makes the treatment complex as it develops a protective coating around antimicrobial agents and the host immunity. A study conducted in Brazil revealed that the percentage of methicillin-resistant strains of *S. aureus* in dairy cow bacterial isolates was more than 25 percent (Freu *et al.*, 2022).

One of the most common causes of most infections, *Escherichia coli* is a widespread Gram-negative bacterium

and forms a considerable portion of the urinary tract infections (UTIs) (Whelan *et al.*, 2023). Similarly, just as it is possible in the case of *S. aureus*, *E. coli* has also become more resistant to general antibiotics and has the capacity of developing persistent strains that makes it harder to eliminate infections. The varied composition of the cell wall of gram-positive and gram-negative bacteria cells, which reduces to the thickness of peptidoglycan layers, thick peptidoglycan in *S. aureus* and thin peptidoglycan below the outer portion of the lipopolysaccharide in *E. coli*, is therefore likely to influence the susceptibility of these bacteria to antimicrobial action contrary to the expectations. The question arises of needing to understand the connection between these structural differences to come up with certain and efficient antimicrobial strategies.

The goals of this review are to synthesize the presently existing data on the antibacterial activity of Fe-doped ZnO nanoparticles and cinnamon essential oil against the two pathogenic bacteria that are among the most critical strains, the mechanisms of action they exert, and the possible ways of synergizing their use in combating the phenomenon of AMR.

Addressing antimicrobial resistance

It is an evolutionary process (determined by the selective pressure of standard antibiotics) that offers antimicrobial resistance (AMR) to any species that possesses a spectrum of adaptive capabilities to deal with the pressure created by a standard intervention. The discussed agents, i.e., Fe-doped ZnO nanoparticles and cinnamon essential oil, may represent a new paradigm of anti-AMR agents since they act through several, non-specific mechanisms (Yudasari *et al.*, 2020).

Due to their unique physicochemical properties, including small size, high surface area, and surface chemistry plasticity, nanoparticles act via multiple biochemical pathways simultaneously. These include direct disruption of cell walls and membranes, induction of oxidative stress in the form of reactive oxygen species (ROS), enzyme inhibition, and interference in nucleic acid synthesis (Godoy-Gallardo *et al.*, 2021). As a multi-level way of action occurs, it is far more difficult to develop resistance to such agents by bacteria than it is to antibiotics. As an example although bacteria can become resistant to silver nanoparticles by aggregation by producing flagellin in *E. coli* or by forming a biofilm in *S. aureus*, the very mechanism of resistance (nanoparticle aggregation) remains significantly more complicated than that of most antibiotics (Hochvaldová *et al.*, 2024). Nanoparticles have a variety of actions and effects that ensure more than one mutation of the bacteria will have to occur at once to neutralize their effects, a less likely evolutionary course of action.

Essential oils, especially cinnamon essential oil, exert their strong antibacterial properties due to a complex blend of essential compounds, which mediate multiple bacterial targets, cinnamaldehyde being the main one (El Atki *et al.*, 2019). The disruption of the cell membrane, metabolic inhibition, and the prevention of biofilm formation allow CEO to have a multi-pronged effect against bacteria that is extremely hard to develop any resistance to due to the low odds of bacteria developing

resistance to multiple compounds and mechanisms at once.

Moreover, genetic mechanisms of nanoparticle and essential oils resistance are usually not the same as those of the conventional antibiotics. The main advantage of these antibacterial components is that they can deliver a broad-spectrum antimicrobial assault to pre-existing resistance since resistance has been repeatedly and unsuccessfully failing all over the globe. This possibility is further extended by the fact that additive systems are available in which synergistic effects may be quantified of Fe doped ZnO combined with the CEO to give more powerful and impervious antimicrobial results that are even harder to counter. This compound effect also obviously supports the urgency of the future decision to invest and develop these new antibacterial components.

Methods of the Fe-doped ZnO nanoparticles production

Iron-doped zinc oxide (Fe-doped ZnO) nanoparticles are prepared to improve the properties of pure ZnO, particularly, the capacity of the antibacterial activity in the visible light (Muşat et al., 2017). Iron doped Zinc oxide nanoparticles are synthesized by various low-cost methods and highly effective techniques. Various studies report different methods of synthesis of Fe-doped ZnO nanoparticles. They are some of the methods mentioned below:

Characterization Techniques

The Fe-doped ZnO nanoparticles are thus characterized in detail with respect to structural, morphology, elemental, and optical properties. Scanning Electron Microscopy (SEM) + Energy-Dispersive X-ray analysis (EDX): The morphology and elemental composition of the products are determined by scanning electron microscope (SEM) with Energy-Dispersive X-ray analyzer (EDX). Moreover, without any hybridization, ZnO nanoparticles can be highly agglomerated and heterogeneous in nature with an average particle size of around 170-20 nm. Iron doping almost

suppresses aggregation, and many of the particles have the shape of a sheet. EDX indicates that zinc, iron and oxygen are effectively loaded into the iron-doped materials.

Mechanisms of Action of Fe-doped ZnO nanoparticles

Fe-doped ZnO nanoparticles possess complex antibacterial mechanisms which mainly include production of reactive oxygen species (despite the high rate of intracellular reactive oxygen species (ROS) production generated by these nanoparticles in our experience, Fe-doped ZnO nanoparticles did not show an increase in intracellular reactive oxygen species (ROS) production when they were added to *Pocria* slept on the submarine there successfully, albeit wastefully, with the additional burden of a thousand pounds (Lakshmi Prasanna *et al.*, 2015).

The extensive generation of ROS, including hydroxyl radicals (OH), superoxide anions ($O_2^{\bullet-}$), and hydrogen peroxide (H_2O_2), is a significant cause of antibacterial activity of ZnO, even in the dark. This ROS formation is mostly facilitated by surface defects, specifically singly ionized oxygen vacancies, which are instrumental in initiating the ROS production process (Singh *et al.*, 2020). A larger segment of these surface defects is available in nanoparticles due to the increased surface area compared to the microparticles, and, as a result, the ROS production increases and, in turn, the antibacterial effects. Introduction of Fe within the ZnO crystal structure may form new impurity levels, adding to the existing overall energy states and resulting in an improved potential to harness solar drive efficiency, which can result in amplified generation of ROS in the presence of visible light. This increased power oxidation of ZnO in the case of Fe-doping also increases its antibacterial effect.

The other important mechanism is the liberation of zinc ions (Zn^{2+}) when the ZnO nanoparticles are exposed to bacteria or other bacterial cells. These released ions can enter bacterial cells and interfere with the metabolic pathways, such as binding the key proteins, DNA, and enzymes (Mendes *et al.*, 2022). This can result in

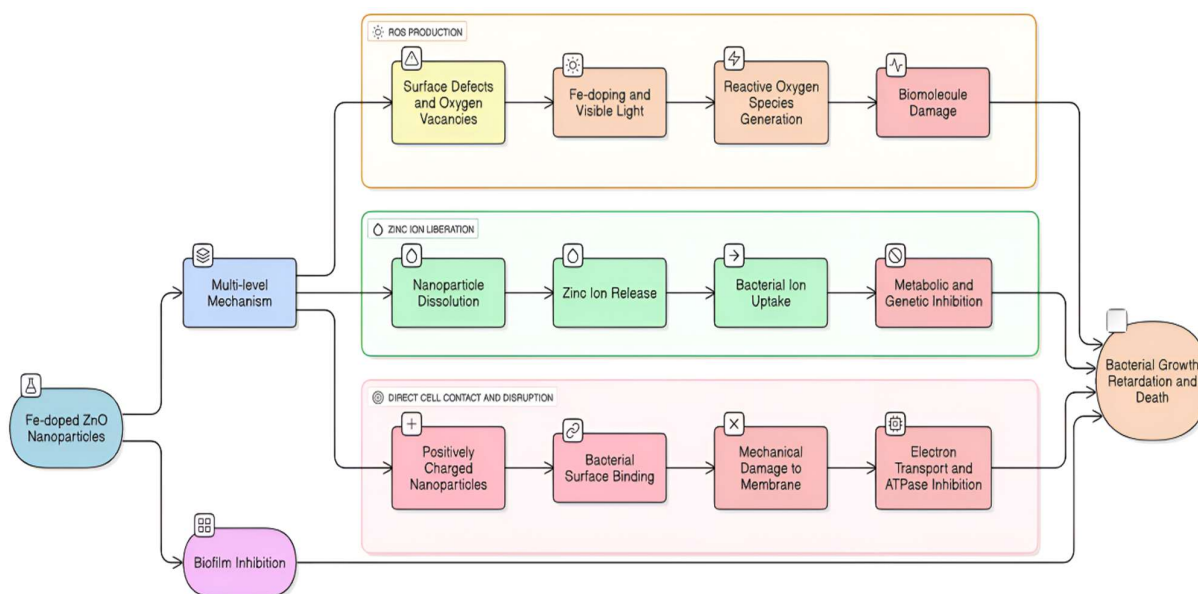


Fig.1: Schematic Diagram of Mechanisms of Action of Fe-doped ZnO nanoparticles.

Table 1: Different synthesis techniques of Iron Doped Zinc Oxide Nanoparticles

Iron Doped ZnO Nanoparticles Variant	Synthesis Method	Source
Polyvinyl pyrrolidone-capped Fe-doped ZnO nanocomposites.	Simple chemical co-precipitation technique	(Sharma <i>et al.</i> , 2016)
Fe-doped ZnO nanosheets	Low-cost wet-chemical method involving citric acid and metal nitrates	(Bavojdan <i>et al.</i> , 2025)
Fe-doped ZnO nanoparticles (from <i>Amaranthus spinosus</i> leaf extract)	Green synthesis using <i>Amaranthus spinosus</i> leaf extract as a reducing agent	(Aiswarya <i>et al.</i> , 2017)
ZnO/Fe ₃ O ₄ /rGO nanocomposites	Hydrothermal method	(Rajan <i>et al.</i> , 2019)
Fe-doped ZnO nanoparticles	Pulsed laser ablation in liquid	(Yudasari <i>et al.</i> , 2020)
Fe-doped ZnO nanoparticles	Sol-gel method	(Hammad <i>et al.</i> , 2013)

mitochondrial enfeeblement, internal spill, and gene expression change, thus resulting in cell growth retardation and death.

The direct contact and interaction with the cell membrane of the bacteria also contribute to the process to some degree. The metal-based nanoparticles are generally positively charged, so they are capable of electrostatically binding to the negatively charged bacterial cell surface, resulting in the penetration through the cell membrane (Sánchez-López *et al.*, 2020). This causes mechanical damage, i.e., puncturing or rupturing of the cell membrane as well as the links in energy metabolism via inhibition of ATPase activity and impairment in electron transport.

Also, Fe-doped ZnO nanoparticles have been shown to prevent bacterial biofilm growth. Biofilms make bacteria even more resistant to antibiotics, drugs, and other antimicrobial agents. ZnO nanoparticles have also been reported to mitigate *S. aureus* biofilm formation by limiting the expression of biofilm-related genes. The capacity of these nanoparticles to inhibit bacterial adhesion to surfaces and their subsequent biofilm development is critical, and therefore, bacterial resistance to single-target antibiotics cannot develop as easily as to Fe-doped ZnO nanoparticles due to the multi-level mechanism of action via ROS generation, liberating ions, and membrane disruption (Ozdal, M., and Gurkok, S., 2022).

Antibacterial Activity of Fe-doped ZnO nanoparticles

Fe-doped ZnO nanoparticles have shown to be more active towards any kind of bacteria Gram-negative such *Escherichia coli* (*E. coli*) and Gram-positive bacteria such as *Staphylococcus aureus* (*S. aureus*) than undoped ZnO nanoparticles against any kind of bacteria (Yudasari *et al.*, 2020).

Using the agar diffusion method, there has been an increased response that Fe-doped ZnO particles have a higher capacity to interfere with *E. coli* growth as opposed to non-doped ZnO. Its antimicrobial activity against *S. aureus* is mostly analogous to *E. coli*, where the antibacterial effects of the two bacteria are nearly similar. As an example, undoped ZnO exhibits greater antimicrobial efficacy under UV light because the band gap must be hit by the UV radiation to create free radicals, whereas doping with Fe allows visible light activity by altering this band gap.

The morphology of ZnO nanoparticles and their size, as well as their concentration, have been known to affect the antibacterial activity of these particles. The smaller particle sizes usually result in higher antibacterial activity because of the greater specific surface area. In the case of undoped ZnO nanoparticles, the Minimum Inhibitory Concentration (MIC) has been stated to be 1 mg/mL in the case of *E. coli*

and 0.5 mg/mL in the case of *S. aureus* (Emami-Karvani *et al.*, 2011). The Zones of Inhibition (ZOI) were 29 mm against *E. coli* and 19 mm against *S. aureus* using undoped ZnO at a 10 mg/mL concentration. Although certain MIC and MBC concentrations of Fe-doped ZnO are not repeatedly stated in the snippets reviewed, the augmentation of antimicrobial activity with the addition of Fe is noted as an improvement across snippets. As an illustration, a work on silver-doped ZnO nanoparticles recorded a ZOI of 19 mm against *S. aureus*, and 15 mm against *E. coli* at 50 mg/mL (Emami-Karvani *et al.*, 2011). Another study demonstrates that a co-doping of zinc oxide nanoparticles (ZnO NPs) with iron and capping chemicals resulted in better structure (smaller 10. 1-17. 8 nm crystallite size, specific Zn-O bond formation), optical (the inhibition of the emission green fraction), and bactericidal (the minimization of the surface defects and the better microbial adsorption) properties (Rao *et al.*, 2023).

ZnO nanoparticles and their doped counterparts are always reported to be more active against Gram-positive rather than Gram-negative species (Slman and A. A. 2012). The reason behind it is generally ascribed to the structures of cell walls: the Gram-positive cell wall that comprises predominantly a thick layer of peptidoglycan is easier to break and disrupt, and the lipopolysaccharide outer membrane of Gram-negative bacteria comes into action to counter such nanoparticle disruption. Nevertheless, Fe-doped ZnO nanoparticles have been exhibited to have greater antibacterial activity against Gram-positive and Gram-negative bacteria as compared to undoped ZnO, signifying that they are of broad interest. An ideal weight ratio of zinc and iron also plays an important role in the antibacterial activities of the combined nanoparticles.

Methods of Cinnamon Essential Oil (CEO) synthesis

Cinnamon essential oil (CEO) is a product naturally formed mostly on the bark of *Cinnamomum cassia* or *Cinnamomum zeylanicum* (Wong *et al.*, 2014). The culmination of its powerful biological activities is mostly owed to the complexity of its chemical composition.

Compositional Analysis: Gas Chromatography-Mass Spectrometry (GC-MS) is the most commonly known method that is applied to determine and measure the number of volatile substances that are contained in the CEO. This study continues to identify cinnamaldehyde as the principal one, which amounts to a very large proportion most of the time, including 92.40 or 82.55 percent in some of the studies. Other articles show a cinnamaldehyde percentage of about 79.74% (Utcharyiakiat *et al.*, 2016). This is mainly due to the large proportion of cinnamaldehyde, which is the main cause of the powerful antimicrobial effect of CEO. In spite of the fact that

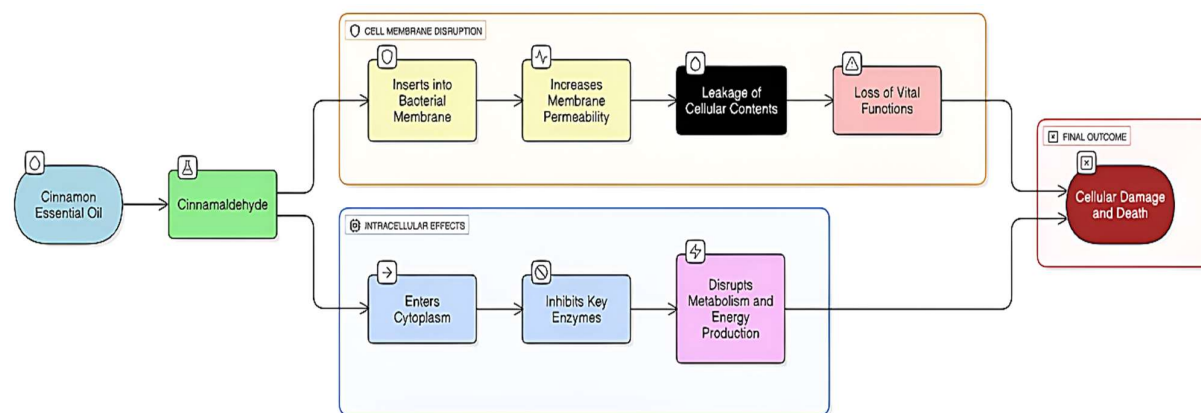


Fig.2: Schematic Diagram of Mechanisms of Action of Cinnamon Essential Oil.

Table 2: Antibacterial Results of differently iron doped ZnO nanoparticles

Nanoparticles concentration	Against <i>S. aureus</i>	Against <i>E. coli</i>	Source
ZnO	N/A	11 mm ZOI at 15 µg concentration	(Aiswarya et al., 2017)
1% doped Fe-ZnO	N/A	12 mm ZOI at 15 µg concentration	(Aiswarya et al., 2017)
Fe-doped 5% ZnO + CA	24 mm ZOI	22 mm ZOI	(Ranathunga et al., 2024)
ZnO + Cellulose acetate	19 mm ZOI	17 mm ZOI	(Ranathunga et al., 2024)

cinnamaldehyde is quantitatively the most significant and active antimicrobial agent, minor constituents of the essential oil, including 2-caryophyllene, eugenol, eugalytol, linalool, benzaldehyde, borneol, and terpenes, can also contribute to the overall activity (Doyle et al., 2019).

Mechanisms of Action of Cinnamon Essential Oil

Cinnamon essential oil (CEO) has a strong antibacterial effect due to its main component, cinnamaldehyde, which functions based on numerous mechanisms related to various cellular actions of bacteria.

Probably one of the most important mechanisms is the disruption of the bacterial cell membrane. Cinnamaldehyde, as well as other phenolic components of essential oils, can easily cross the bacterial cell wall and insert itself into the phospholipid bilayer of the cytoplasmic membrane. This causes a local change of permeability in the cell membrane and destabilizes the lipid bilayer, thus resulting in a morphological change in the bacterial cell, such as swelling.

This increased permeability of membranes allows for loss of small solutes, proteins, nucleic acids, and other intracellular molecules into the extracellular space (Pai et al., 2023). The latter can be inferred from a strong increase of the electrical conductivity of bacterial suspensions upon treatment with CEO.

Apart from the structural damages, the cinnamon essential oil disrupts the bacterial functions. It can cause significant membrane potential depolarization, which is needed for ATP synthesis in the bacterial cell. This reduction of metabolic activity by a factor of at least 3 to 5 represents cellular processes important to the survival and growth of

the bacteria. Cinnamaldehyde specifically could inhibit the intracellular ATP ATPase activity, and consequently might inhibit the availability of energy for the cells. Subsequently, it can constitute action on the intracellular proteins and hormones, disturbance of the normal cell division (causing division arrest) and bacteriostatic action. The antimicrobial resistance mechanism of CEO also affects bacterial growth by inhibiting biofilm development. The CEO can eliminate and inhibit the growth of mature bacterial biofilms; this is the most important benefit of its use in chronic infection (Pai et al., 2023).

Further, the antibacterial activity of CEO and cinnamaldehyde can be linked to the antioxidant activity. These chemicals are highly active antioxidants, which may be related to their broad-spectrum bacterial effects, but the specific interaction between the antioxidant and the direct antimicrobial actions remains to be elucidated.

Antibacterial Activity of Cinnamon Essential Oil against *E. coli* and *S. aureus*

Cinnamon essential oil (CEO) has proved to be a good antibacterial agent against Gram-negative *Escherichia coli* (*E. coli*) as well as Gram-positive *Staphylococcus aureus* (*S. aureus*) (Zhao et al., 2023). Indeed, the Minimum Inhibitory Concentration (MIC) values of CEO have ranged according to different studies and strains, but one can conclude that activity is very good. As an example, MICs of CEO were reported at 1.0 mg/mL against *E. coli* and *S. aureus* in one report and at 4.88 mcg/mL against both organisms in another one. Some of the research has discovered MICs of 780.00 µg/ ml against *E. coli* and 3125.00 µg/ ml against *S. aureus* (Raeisia et al., 2015). However, 78.13 ppm against *E. coli* and 1250.00 ppm against *S. aureus* were found in Chinese cinnamon bark oil (Zhao et al., 2023). This fluctuation makes it more pertinent to standardize the composition of essential oils and their test measures.

The bactericidal nature of the CEO can also be depicted in its Minimum Bactericidal Concentration (MBC) values. It has also been reported that 4.0 mg/mL against *E. coli* and 2.0 mg/mL against *S. aureus*, and 625.00 µg/mL against *E. coli* and *S. aureus*. All these results suggest the fact that the CEO not only suppresses the growth but also effectively kills these pathogenic bacteria (Lopez-Romero et al., 2015).

In the different studies, this observation is always made that there is a dimensional vulnerability of the two bacterial species. *S. aureus* is, in most cases, more sensitive to CEO as compared to *E. coli* (Raeisi *et al.*, 2015). But in some studies, on essential oils of compounds based on Chinese cinnamon bark oil and oregano oil, the sensitivity of *E. coli* was found to be more pronounced. Part of this difference is due to the variation in the cell wall structures of Gram-positive and Gram-negative bacteria. Gram-negative *E. coli* has a thinner wall and less peptidoglycan, which in some instances made the anti-bacterial properties of CEO also depend on the concentration used, and usually, the greater the inhibitory effect (Zhao *et al.*, 2023). Different types of Cinnamon essential oil variants have varying antibacterial activity against these bacteria.

Evidence of synergy and combined effect in different studies

Although Fe-ZnO + cinnamon EO has not been tested so far, there are several lines of evidence suggesting some synergy:

ZnO NPs + Essential Oils

There are several reports that the antimicrobial activity is strongly increased after the combination of ZnO NPs with essential oils. For instance, Motelica *et al.* (2023) loaded ZnO NPs with different oils (including cinnamon oil) and reported a synergistic antibacterial effect: ZnO-EO hybrids were more efficient against the bacteria than one of the components entirely. Similarly, Babapour *et al.* (2021) included ZnO NPs and Fennel oil in starch films and found good synergy properties: as the loading amount of ZnO or Fennel oil increased, the antimicrobial activity of the films increased, and ZnO + oil demonstrated much stronger inhibition than ZnO or oil alone. In other words, ZnO NPs can act as the surface carriers that not only store EO volatiles but also synergistically destroy cells (causing greater efficacy). (Motelica *et al.*, 2023)

Fe-doped ZnO vs. Pure ZnO

Direct comparative studies between Fe-ZnO and ZnO with no individual doping reveal the increase in bactericidal activity elicited by Fe-doping. As described above, Devi *et al.* reported that Fe-ZnO (Fe-doped ZnO) resulted in bigger *E. coli* ZOI than unmodified ZnO (P ZnO). This is consistent with others; for example, Xu *et al.* had found that Fe-ZnO has a stronger inhibition against many bacteria than unmodified ZnO, as reported previously (Zones 29-32 mm for Fe-ZnO vs. ~25 mm for ZnO). We also show that Fe doping decreases the Zn²⁺ release and decreases the resistance formation. These comparisons suggest that if pure ZnO can synergize with an EO, Fe-ZnO will be able to as well (possibly with even better efficiency because of its greater activity).

Cinnamon EO + other nanoparticles: CEO was formulated with other metal NPs. Recently, Trieu *et al.* (2024) reported the preparation of Ag nanoparticles, using CEO as a green reducing/stabilizing agent; these "cinnamon-capped" AgNPs exhibited a high inhibition against *S. aureus* and *E. coli*. Lopez-Cano *et al.* (2023) also chemically grafted CEO on several oxide NPs. They found that CEO-modification had transferred antimicrobial

properties to the NPs: CEO-coated Al₂O₃ NPs became active against Gram-negative bacteria, while pure Al₂O₃ was inert (however, CEO did not bind well to TiO₂ or CaCO₃ NPs in their work, so those showed little effect). Although cinnamon oil has not yet been challenged with ZnO or Fe-ZnO, these studies showed that cinnamon oil also synergizes against metal-based antimicrobials if appropriately mixed.

From those examples (ZnO + EO, Fe-ZnO vs ZnO, CEO + Ag/ Al₂O₃), we speculate that the combined actions of cinnamon EO and Fe-ZnO NPs could be synergistic: the ROS-based killing of ZnO would be complemented by the membrane-damaging EO. Since Fe appears to increase ZnO activity (particle size decrease, more defects), and EO (cinnamaldehyde) permeabilizes the cell, then ZnO uptake might be increased by EO. Although no direct study has tested this combination, the evidence from the above studies (ZnO/EO and NP/EO) strongly suggests that a combined Fe-ZnO + cinnamon oil treatment could outperform either treatment alone.

Comparative Activity vs *S. aureus* and *E. coli*

Both Fe-ZnO NPs and cinnamon EO inhibit *S. aureus* and *E. coli*, but their relative potencies differ.

Fe-ZnO NPs

Studies show *E. coli* is often more inhibited than Gram+ bacteria. Fe-ZnO gave a larger zone against *E. coli* than against a Gram-positive (*B. safensis*) (Aiswarya *et al.*, 2017). In one report, 1 wt% Fe-ZnO gave ~19 mm ZOI against *S. aureus* while *E. coli* zones were larger (Abebe *et al.*, 2020). Fe-ZnO MICs against both species are typically on the order of ~10–100 µg/mL (depending on assay conditions).

Cinnamon EO

As noted, *S. aureus* is generally more sensitive. In one study, it was found that MICs ≈ were 3125 µg/mL for *S. aureus* vs 780 µg/mL for *E. coli*, and ZOIs were 28.5 mm vs 21.7 mm (Raeisi *et al.*, 2017). Thus, at equal concentrations, CEO produces a larger inhibition on *S. aureus*. Typically, CEO MICs are a few mg/mL, while ZnO NPs inhibit at tens of µg/mL.

Pure ZnO for comparison

In comparison with the Fe-ZnOs and CEO, pure ZnO NPs alone also inhibit both organisms, often with ZOI ~20–25 mm for *S. aureus* at 20 mm for *E. coli* ZnO, but Fe-ZnO usually performs better as noted (Hao *et al.*, 2024).

Challenges and Future Directions

Although the antibacterial potential of Fe-doped ZnO nanoparticles and cinnamon essential oil implies their very effective potential clinical and commercial distribution, there are still numerous difficulties to overcome to achieve this goal (Mondal *et al.*, 2024). These issues mainly correlate to toxicity, standardization, and the shift of in vivo to in vitro efficacy.

Toxicity and Biocompatibility

A major consideration with all nanomaterials is their possible cytotoxicity at certain concentrations and long-term biocompatibility with human cells and tissues

Table 3: Antibacterial results of different types of Cinnamon Essential Oil

Cinnamon Oil Type	Bacteria	Antibacterial Results	Source
Cinnamomum burmannii extract	Staphylococcus aureus	In vitro inhibition with a minimum bactericidal concentration (MBC) of 5% and an inhibitory zone of 6.84 ± 0.68 mm.	(Parisa <i>et al.</i> , 2019)
Cinnamomum burmannii extract	Escherichia coli	In vitro inhibition with an MBC of 10% and an inhibitory zone of 5.69 ± 0.69 mm.	(Parisa <i>et al.</i> , 2019)
Cinnamon Essential Oil (high cinnamaldehyde content)	Escherichia coli	Minimum inhibition concentration (MIC) of 1.0 mg/ml and minimum bactericidal concentration (MBC) of 4.0 mg/ml.	(Zhang <i>et al.</i> , 2016)
Cinnamon Essential Oil (high cinnamaldehyde content)	Staphylococcus aureus	Minimum inhibition concentration (MIC) of 1.0 mg/ml and the minimum bactericidal concentration (MBC) of 2.0 mg/ml.	(Zhang <i>et al.</i> , 2016)
trans-Cinnamaldehyde (the main ingredient of cinnamon oil)	Escherichia coli	Showed great antibacterial activity with a minimum inhibitory concentration (MIC) of 0.25 µL/mL and a minimum bactericidal concentration (MBC) of 0.5 µL/mL.	(Zhang <i>et al.</i> , 2015)
trans-Cinnamaldehyde (the main ingredient of cinnamon oil)	Staphylococcus aureus	Showed great antibacterial activity with a minimum inhibitory concentration (MIC) of 0.25 µL/mL and a minimum bactericidal concentration (MBC) of 0.5 µL/mL.	(Zhang <i>et al.</i> , 2015)

Table 4: Synergistic and individual antibacterial results from key studies

Agent	<i>S. aureus</i> Activity	<i>E. coli</i> Activity	Reference
Fe–ZnO NPs	ZOI ≈ 19 mm (PVA composite. ~tens µg/mL (strong killing)	ZOI is larger MIC (stronger killing vs <i>E. coli</i>)	Devi <i>et al.</i> (2017)
Cinnamon EO (CEO)	ZOI ≈ 28.5 mm; MIC ~3.1 mg/mL	ZOI ≈ 21.7 mm; MIC ~0.78 mg/mL	Raeisi <i>et al.</i> (2015)
Pure ZnO NPs (for mM ZnO) context)	ZOI ~26 mm (20 ~6.25 µg/mL (4 nm ZnO)	ZOI ~22 mm MIC (higher inoculum)	Hao <i>et al.</i> (2024)

(Kyriakides *et al.*, 2021). ZnO nanoparticles were considered to be non-toxic to human cells, though other studies observed that they are cytotoxic at some concentrations and deposited in organs such as the spleen, liver, and lungs, causing eventual organ damage (Ng *et al.*, 2017). Low-intensity interactions in vitro are frequently out of focus, requiring much more detailed examination. The environmental release of the antimicrobial nanoparticles is of additional concern because they can affect the positive microbiota and ecosystems (Khanna *et al.*, 2021). Future studies should focus on detailed toxicological measurements, a part of which should be in vivo studies, to determine effective and safe dose rates and minimal disturbance to the health of germ-free human microbiomes.

Standardization and Optimization

On the one hand, the diversity of the antibacterial activities of nanoparticles and essential oils is reported; on the other, the differences among the reported antibacterial activities of different sensorial approaches highlights the lack of consensus among standardization. At the same time, the size, shape, surface charge, composition, method of production and the type of microbe have a significant impact on the antimicrobial performance of nanoparticles (Wang *et al.*, 2017). In terms of essential oils, parameters such as concentration of the active components (Nair *et al.*, 2022 in the case of cinnamaldehyde), along with the proportions play an important role.

Shifting towards In Vivo Experiments and Clinical Translation

In nanoparticle technology, there is significant gap that is present in the current and available research is as the current research is largely in vitro. Cell culture data can only be used to estimate antibacterial activity, and

laboratory models are useful only to determine mechanisms, as they do not reflect the complicated in vivo situation accurately (Hossain *et al.*, 2024). The biokinetics, bioavailability, tissue distribution, and clearance rates of these agents are urgently needed to be studied by in vivo trials. This involves in vitro interaction with host immune systems, stability in biological fluids, and long-term effects. Although metal-based nanoparticle drugs are under clinical trial in several cases, they remain a long way from clinical practice because their extensive use will require strong data on the safety of the drugs and their effectiveness in living organisms (Baranwal *et al.*, 2023). There should also be strict regulations that approve and monitor the use of antimicrobial nanoparticles in order to be safe and effective.

Cost of development and resistance

The cost of manufacturing and use of the nanoparticles could be high compared to the traditional medicine, and this has been a factor that prevents their mass use, for now (Ying, 2022). Moreover, nanoparticles and essential oils also present a multi-pronged attack but, unlike antibiotics, there is a suspicion that despite the lethal or sub-lethal effects of these mechanisms, selection pressures could still allow the emergence of microbial resistance. Therefore, it is important to track the development of resistance and to find ways to prevent horizontal transfer of resistance mechanisms (Munita *et al.* 2019). Therefore, future research should be focused on these issues that will benefit from interdisciplinary research, the development of new synthesis strategies, in vivo studies and even the development of specific principles of design. The integrative approach as such will be of crucial importance to realize the potential of Fe-doped ZnO nanoparticles and cinnamon essential oil for full therapeutic effectiveness in the fight against worldwide AMR.

Conclusion

Antimicrobial resistance (AMR) is global health issue that calls upon the inevitability of novel, and effective anti-bacterial strategies. This review has critically looked at the potential success of both iron doped zinc oxide (Fe-doped ZnO) nanoparticles and cinnamon essential oil (CEO) as a valid replacement or addition to the conventional antibiotics in treatment of *Staphylococcus aureus* and *Escherichia coli*.

Fe-doped ZnO nanoparticles are even better than the non-doped ZnO nanoparticles due to its reduced band gap to be observed to perform better as an antibacterial agent against *S. aureus* and *E. coli* under visible light conditions. Their multimedia activities involve extreme redox generation of ROS, havoc deposition of Zn²⁺ ions and ecological thinness of membrane and basic inhibition of biofilm generation. Competitive advantage offered by doping reveals an avenue toward a selection of material that demonstrates better antimicrobial activities.

The total disruption of the bacteria cell membrane by cinnamaldehyde, the active constituent compound of Cinnamon essential oil effective release of all the intracellular vital contents, and the resultant effective reduction of local metabolism, and consequent, potent and strong antibacterial activities. It is an effective natural antimicrobial agent, with multi-target effects, anti-oxidative effects, and the ability to hinder biofilm formation; so, it will be less susceptible to upcoming points of resistance formation.

Another important observation of this analysis is that an extreme advantage is mixing these agents. Examples of synergistic possibilities of Fe-doped ZnO nanoparticles as a combination with cinnamon essential oil, inter alia, might lead to the mass attack on bacteria which magnifies the effect of the antibacterial effects, and which blocks the biofilm formation which stops the persistence of these bacteria largely. Such a synergy between both nanotechnology and natural product chemistry would serve as a road map to help develop effective antimicrobial systems which will pose little or no resistance to the bacteria through evolutionary alterations.

Despite this promises of massive potential, they still require validation until they can be widely used, and validation also includes complete toxicological assessment, standard synthetic syntheses, testing procedures, and extensive in vivo experimentation to reduce the incongruity between the laboratory and clinical translation. The problem of extra high cost of production and stabilization of nanoparticles and strict regulation also should be examined.

In conclusion, Fe-doped zinc oxide nanoparticles, cinnamon essential oil, and the combination of the two proved to be fascinating prospects in the ongoing global fight against antimicrobial resistance. Their extensive diversity of both complementary and even synergistic processes of action confers upon them new and effective ammunition against recurring bacteria challenges and provide the antecedent to a new generation of viable and sustainable anti-microbial strategies.

DECLARATION

Funding: This research was not supported by national or international funding agency.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgement: None.

Availability of Data and Material: The data regarding this study is included in the paper which can be obtained On reasonable request from corresponding author.

Ethics Statement: The study was carried out according to guidelines mentioned for the welfare and use of study animals for research purposes.

Author's Contribution: MMM, MA: Conceptualization, Methodology, Data curation, Writing-original draft. Visualization, and Validation. ZS and SS: Writing-review and editing, Formal analysis, Software.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript. Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

- Abdelghafar A, Yousef N and Askoura M, 2022. Zinc oxide nanoparticles reduce biofilm formation, synergize antibiotics action and attenuate *Staphylococcus aureus* virulence in host; an important message to clinicians. *BMC Microbiology*, 22(1):244.
- Abebe B, Zereffa EA, Tadesse A and Murthy HA, 2020. A review on enhancing the antibacterial activity of ZnO: Mechanisms and microscopic investigation. *Nanoscale Research Letters*, 15(1):190.
- Adesina AO, 2025. A Facile Synthesis Approach for Iron-Doped Zinc Oxide Nanoparticles with Enhanced Antibacterial Properties. *Journal of Applied Life Sciences International*, 28(3):1-13.
- Aiswarya DS, Harshiny M, Udaykumar S, Gopinath P and Matheswaran M, 2017. Strategy of metal iron doping and green-mediated ZnO nanoparticles: dissolubility, antibacterial and cytotoxic traits. *Toxicology Research*, 6(6):854-865.
- Algammal AM, Hetta HF, Elkelish A, et al., 2020. Methicillin-Resistant *Staphylococcus aureus* (MRSA): one health perspective approach to the bacterium epidemiology, virulence factors, antibiotic-resistance, and zoonotic impact. *Infection and Drug Resistance*, 13:3255-3265.
- Azhar A, Rasool S, Haque A, et al., 2017. Detection of high levels of resistance to linezolid and vancomycin in *Staphylococcus aureus*. *Journal of Medical Microbiology*, 66(9):1328-1331.
- Babapour H, Jalali H and Mohammadi Nafchi A, 2021. The synergistic effects of zinc oxide nanoparticles and fennel essential oil on physicochemical, mechanical, and antibacterial properties of potato starch films. *Food Science and Nutrition*, 9(7):3893-3905.
- Balouiri M, Sadiki M, and Ibensouda SK, 2016. Methods for in vitro evaluating antimicrobial activity: A review. *Journal of pharmaceutical analysis*, 6(2): 71-79.
- Baranwal J, Barse B, Di Petrillo A, Gatto G, Pilia L, and Kumar A, 2023. Nanoparticles in cancer diagnosis and treatment. *Materials*, 16(15): 5354.
- Bavojdan HH, Ghorbanpour M, and Alatae MJA, 2025. Sustainable Synthesis and Characterization of Iron-Doped Zinc Oxide Nanosheets for Antibacterial Activity. *Journal of Water and Environmental Nanotechnology*, 10(2): 152-160.
- Bavojdan HH, Ghorbanpour M, and Alatae MJA, 2025. Sustainable Synthesis and Characterization of Iron-Doped Zinc Oxide Nanosheets for Antibacterial Activity. *Journal of Water and Environmental Nanotechnology*, 10(2): 152-160.

- El Atki Y, Aouam I, El Kamari F, Taroq A, Nayme K, Timinouni M, and Abdellaoui A, 2019. Antibacterial activity of cinnamon essential oils and their synergistic potential with antibiotics. *Journal of Advanced Pharmaceutical Technology and Research*, 10(2): 63-67.
- Emami-Karvani Z, and Chehrizi P. (2011). Antibacterial activity of ZnO nanoparticle on gram-positive and gram-negative bacteria. *African Journal of Microbiol Research*, 5(12): 1368-1373.
- Feßler AT, Kadlec K, Hassel M, Hauschild T, Eidam C, Ehricht R, and Schwarz S, 2011. Characterization of methicillin-resistant *Staphylococcus aureus* isolates from food and food products of poultry origin in Germany. *Applied and Environmental Microbiology*, 77(20): 7151-7157.
- Freu G, Tomazi T, Filho AF, Heinemann, MB, and Dos Santos MV, 2022. Antimicrobial resistance and molecular characterization of *Staphylococcus aureus* recovered from cows with clinical mastitis in dairy herds from southeastern Brazil. *Antibiotics*, 11(4): 424.
- Hammad TM, Griesing S, Wotocek M, Kuhn S, Hempelmann R, Hartmann U, and Salem JK, 2013. Optical and magnetic properties of Fe-doped ZnO nanoparticles prepared by the sol-gel method. *International Journal of Nanoparticles*, 6(4): 324-337.
- Hannachi E, Khan FA, Slimani Y, Rehman S, Trabelsi Z, Akhtar S, and Al-Suhaimi EA, 2022. In vitro antimicrobial and anticancer peculiarities of ytterbium and cerium Co-doped zinc oxide nanoparticles. *Biology*, 11(12): 1836.
- Hao Y, Wang Y, Zhang L, Liu F, Jin Y, Long J and Yang H, 2024. Advances in antibacterial activity of zinc oxide nanoparticles against *Staphylococcus aureus*. *Biomedical Reports*, 21(5): 161.
- Hao Y, Wang Y, Zhang L, Liu F, Jin Y, Long J and Yang H, 2024. Advances in antibacterial activity of zinc oxide nanoparticles against *Staphylococcus aureus*. *Biomedical Reports*, 21(5): 161.
- Hochvaldová L, Panáček D, Válková L, Večeřová R, Kolář M, Pruček R and Panáček A, 2024. *E. coli* and *S. aureus* resist silver nanoparticles via an identical mechanism, but through different pathways. *Communications Biology*, 7(1): 1552.
- Hossain TJ, 2024. Methods for screening and evaluation of antimicrobial activity: A review of protocols, advantages, and limitations. *European Journal of Microbiology and Immunology*, 14(2): 97-115.
- Hrenovic J, Milenkovic J, Daneu N, Kepcija RM, and Rajic N. (2012). Antimicrobial activity of metal oxide nanoparticles supported onto natural clinoptilolite. *Chemosphere*, 88(9): 1103-1107.
- Iseppi R, Truzzi E, Sabia C, and Messi P, 2024. Efficacy and synergistic potential of cinnamon (*Cinnamomum zeylanicum*) and clove (*Syzygium aromaticum* L. Merr. and Perry) essential oils to control food-borne pathogens in fresh-cut fruits. *Antibiotics*, 13(4): 319.
- Khanna K, Kohli SK, Handa N, Kaur H, Ohri P, Bhardwaj R and Ahmad P, 2021. Entrapping the impact of engineered nanoparticles on soil microbiome: A concentric approach towards environmental risks and cogitation. *Ecotoxicology and Environmental Safety*, 222, 112459.
- Kyriakides TR, Raj A, Tseng TH, Xiao H, Nguyen R, Mohammed FS and Sheu WC, 2021. Biocompatibility of nanomaterials and their immunological properties. *Biomedical Materials*, 16(4): 042005.
- Lakshmi Prasanna V, and Vijayaraghavan R, 2015. Insight into the mechanism of antibacterial activity of ZnO: surface defects mediated reactive oxygen species even in the dark. *Langmuir*, 31(33): 9155-9162.
- López-Cano AA, Martínez-Aguilar V, Peña-Juárez MG, López-Esparza R, Delgado-Alvarado E, Gutiérrez-Castañeda E and Gonzalez-Calderon JA, 2023. Chemically modified nanoparticles for enhanced antioxidant and antimicrobial properties with cinnamon essential oil. *Antioxidants*, 12(12): 2057.
- Lopez-Romero JC, González-Ríos H, Borges A, and Simões M, 2015. Antibacterial effects and mode of action of selected essential oils components against *Escherichia coli* and *Staphylococcus aureus*. *Evidence-Based Complementary and Alternative Medicine*, 2015(1): 795435.
- Mondal SK, Chakraborty S, Manna S, and Mandal SM, 2024. Antimicrobial nanoparticles: current landscape and future challenges. *RSC Pharmaceutics*, 1(3): 388-402.
- Motelica L, Vasile BS, Ficai A, Surdu AV, Ficai D, Oprea OC and Dobre AA, 2023. Antibacterial activity of zinc oxide nanoparticles loaded with essential oils. *Pharmaceutics*, 15(10): 2470.
- Motelica Ludmila and Ficai Denisa and Oprea Ovidiu and Ficai Anton and Trusca Roxana and Ungureanu Elena and Dobre Alina, 2024. Polyethylene / zinc oxide/ cinnamon essential oil composite films -a novel antimicrobial packaging for tomatoes.
- Mphahlele MP, Oguttu JW, Petzer IM and Qekwana DN, 2020. Prevalence and antimicrobial drug resistance of *Staphylococcus aureus* isolated from cow milk samples. *Veterinary World*, 13(12): 2736.
- Munita JM and Arias CA, 2016. Mechanisms of antibiotic resistance. *Microbiol Spectr* 4.
- Muşat V, Ibănescu M, Tutunaru D and Potecaşu F, 2017. Fe-Doped ZnO Nanoparticles: Structural, Morphological, Antimicrobial and Photocatalytic Characterization. *Advanced Materials Research*, 1143, 233-239.
- Nair A, Mallya R, Suvarna V, Khan TA, Momin M, and Omri A, 2022. Nanoparticles—Attractive carriers of antimicrobial essential oils. *Antibiotics*, 11(1): 108.
- Ozdam M and Gurkok S, 2022. Recent advances in nanoparticles as antibacterial agent. *ADMET and DMPK*, 10(2): 115-129.
- Pai L, Patil S, Liu S and Wen F, 2023. A growing battlefield in the war against biofilm-induced antimicrobial resistance: insights from reviews on antibiotic resistance. *Frontiers in Cellular and Infection Microbiology*, 13, 1327069.
- Parisa N, Islami RN, Amalia E, Mariana M and Rasyid RSP, 2019. Antibacterial activity of cinnamon extract (*Cinnamomum burmannii*) against *Staphylococcus aureus* and *Escherichia coli* in vitro. *Bioscientia Medicina: Journal of Biomedicine and Translational Research*, 3(2): 19-28.
- Patra JK, Das G, Fraceto LF, Campos EVR, Rodriguez-Torres MDP, Acosta-Torres LS and Shin HS, 2018. Nano based drug delivery systems: recent developments and future prospects. *Journal of Nanobiotechnology*, 16(1): 71.
- Prabhu S, and Poulouse EK, 2012. Silver nanoparticles: mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. *International Nano Letters*, 2(1): 32.
- Raeisi M, Tajik H, Yarahmadi A, and Sanginabadi S, 2015. Antimicrobial effect of cinnamon essential oil against *Escherichia coli* and *Staphylococcus aureus*. *Health Scope*, 4(4).
- Raghunath A and Perumal E, 2017. Metal oxide nanoparticles as antimicrobial agents: a promise for the future. *International journal of antimicrobial agents*, 49(2): 137-152.
- Rajan SA, Khan A, Asrar S, Raza H, Das RK and Sahu NK, 2019. Synthesis of ZnO/Fe₃O₄/rGO nanocomposites and evaluation of antibacterial activities towards *E. coli* and *S. aureus*. *IET Nanobiotechnology*, 13(7): 682-687.
- Ranathunga K, Yapa P, Munaweera I, Weerasekera MM and Sandaruwan C, 2024. Preparation and characterization of Fe-ZnO cellulose-based nanofiber mats with self-sterilizing photocatalytic activity to enhance antibacterial applications under visible light. *RSC Advances*, 14(26): 18536-18552.
- Rao YS, Parajuli D, Rao MS, Ramakrishna A, Ramanjaneyulu K,

- Mammo TW and Murali N, 2023. Effect of Fe doped and capping agent-structural, optical, luminescence, and antibacterial activity of ZnO nanoparticles. *Chemical Physics Impact*, 7, 100270.
- Salam MA, Al-Amin MY, Salam MT, Pawar JS, Akhter N, Rabaan AA and Alqumber MA. (2023, July). Antimicrobial resistance: a growing serious threat for global public health. In *Healthcare* (Vol. 11, No. 13, p. 1946). MDPI.
- Sánchez-López E, Gomes D, Esteruelas G, Bonilla L, Lopez-Machado AL, Galindo R and Souto EB, 2020. Metal-based nanoparticles as antimicrobial agents: an overview. *Nanomaterials*, 10(2): 292.#
- Sharma N, Jandaik S, Kumar S, Chitkara M, and Sandhu IS, 2016. Synthesis, characterisation and antimicrobial activity of manganese-and iron-doped zinc oxide nanoparticles. *Journal of Experimental Nanoscience*, 11(1): 54-71.
- Siddiqi KS, Ur Rahman A, Tajuddin N, and Husen A, 2018. Properties of zinc oxide nanoparticles and their activity against microbes. *Nanoscale research letters*, 13(1): 141.
- Singh R, Cheng S, and Singh S, 2020. Oxidative stress-mediated genotoxic effect of zinc oxide nanoparticles on *Deinococcus radiodurans*. *3 Biotechnologies*, 10(2): 66.
- Slman AA. (2012). Antibacterial activity of ZnO nanoparticle on some gram-positive and gram-negative bacteria. *Iraqi Journal of Physics*, 10(18): 5-10.
- Tang KL, Caffrey NP, Nóbrega DB, Cork SC, Ronksley PE, Barkema HW and Ghali WA, 2017. Restricting the use of antibiotics in food-producing animals and its associations with antibiotic resistance in food-producing animals and human beings: a systematic review and meta-analysis. *The Lancet Planetary Health*, 1(8): e316-e327.
- Tang KWK, Millar BC and Moore JE, 2023. Antimicrobial resistance (AMR). *British Journal of Biomedical Science*, 80, 11387.
- Taylor TA and Unakal CG, 2017. *Staphylococcus aureus* infection.
- Trieu QA, Nguyen NPY and Bui TH, 2024. Cinnamon Essential Oil-Mediated Synthesis of Silver Nanoparticles and Examination of Their Antibacterial Activity.
- Utchariyakiat I, Surassmo S, Jaturanpinyo M, Khuntayaporn P, and Chomnawang MT, 2016. Efficacy of cinnamon bark oil and cinnamaldehyde on anti-multidrug resistant *Pseudomonas aeruginosa* and the synergistic effects in combination with other antimicrobial agents. *BMC Complementary and Alternative Medicine*, 16(1): 158.
- Van Boeckel TP, Brower C, Gilbert M, Grenfell BT, Levin SA, Robinson TP and Laxminarayan R, 2015. Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences*, 112(18): 5649-5654.
- Visan AI, and Negut I, 2024. Coatings based on essential oils for combating antibiotic resistance. *Antibiotics*, 13(7): 625.
- Wang L, Hu C, and Shao L, 2017. The antimicrobial activity of nanoparticles: present situation and prospects for the future. *International Journal of Nanomedicine*, 1227-1249.
- Whelan S, Lucey B and Finn K, 2023. Uropathogenic *Escherichia coli*(UPEC)-associated urinary tract infections: the molecular basis for challenges to effective treatment. *Microorganisms*, 11(9): 2169.
- Wong YC, Ahmad-Mudzaqqir MY and Wan-Nurdiyana WA, 2014. Extraction of essential oil from cinnamon (*Cinnamomum zeylanicum*). *Oriental Journal of Chemistry*, 30(1): 37.
- Yin H, Lu Y, Chen R, Orrell-Trigg R, Gangadoo S, Chapman J and Truong VK, 2024. Cytotoxicity and Antimicrobial Efficacy of Fe-, Co-, and Mn-Doped ZnO Nanoparticles. *Molecules*, 29(24): 5966.
- Ying S, Guan Z, Ofoegbu PC, Clubb P, Rico C, He F and Hong, J, 2022. Green synthesis of nanoparticles: Current developments and limitations. *Environmental Technology and Innovation*, 26, 102336.
- Yudasari N, Suliyanti MM and Imawan C, 2020. Antibacterial activity of Fe-doped ZnO nanoparticles synthesised via pulsed laser ablation in liquid against *Staphylococcus Aureus*. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 11(2): 025003.
- Zhang YB, Liu XY, Jiang PP, Li WD and Wang YF, 2015. Mechanism and antibacterial activity of cinnamaldehyde against *Escherichia coli* and *Staphylococcus aureus*. *Modern Food Science and Technology*, 31: 31-35.
- Zhang Y, Liu X, Wang Y, Jiang P and Quek S, 2016. Antibacterial activity and mechanism of cinnamon essential oil against *Escherichia coli* and *Staphylococcus aureus*. *Food control*, 59: 282-289.
- Zhao A, Zhang Y, Li F, Chen L and Huang X, 2023. Analysis of the antibacterial properties of compound essential oil and the main antibacterial components of unilateral essential oils. *Molecules*, 28(17): 6304.